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Appendix

3.0 Exhaust Muffler Design Principles

3.1 Basic Concepts

Internal combustion engines are typically equipped with an exhaust muffler to suppress the acoustic pulse generated by the combustion process. A high intensity pressure wave generated by combustion in the engine cylinder propagates along the exhaust pipe and radiates from the exhaust pipe termination. The pulse repeats at the firing frequency of the engine which is defined by $f = (\text{engine rpm} \times \text{number of cylinders}) / 120$ for a four stroke engine. The frequency content of exhaust noise is dominated by a pulse at the firing frequency, but it also has a broadband component to its spectrum which extends to higher frequencies. Measurements of the exhaust pipe pressure pulse on a Continental O-200 engine [4] show that the majority of the pulse energy lies in the frequency range of 0-600 Hz. Exhaust mufflers are designed to reduce sound levels at these frequencies.

In general, sound waves propagating along a pipe can be attenuated using either a dissipative or a reactive muffler. A dissipative muffler uses sound absorbing material to take energy out of the acoustic motion in the wave, as it propagates through the muffler. Reactive silencers, which are commonly used in automotive applications, reflect the sound waves back towards the source and prevent sound from being transmitted along the pipe. Reactive silencer design is based either on the principle of a Helmholtz resonator or an expansion chamber, and requires the use of acoustic transmission line theory.

In a Helmholtz resonator design a cavity is attached to the exhaust pipe. At a specific frequency the cavity will resonate and the waves in the exhaust pipe are reflected back towards the source. However there are also pass band frequencies where the resonator has no effect and so resonator muffler design is targeted to specific frequencies where the majority of the attenuation is required. In some designs, the muffler has several resonators of different sizes to target a range of frequencies.

Expansion chamber mufflers reflect waves by introducing a sudden change in cross sectional area in the pipe. They do not have the high attenuation of the Hemholtz resonator, but have a broadband frequency characteristic, with pass bands when half the acoustic wavelength equals the cavity length. Their performance also deteriorates at higher frequencies when the cross axis dimension of the muffler is 82% of the acoustic wavelength (Davis, Stokes, Moore and Stevens [5]). Some expansion chamber muffler systems are also packed with sound absorbing material which helps to improve the high frequency attenuation.

In all muffler designs the tailpipe length can have an important effect. The tailpipe itself acts as a resonant cavity that couples with the muffler cavity. The attenuation characteristics of a muffler are modified if the design tailpipe is not used. Also, the effect of exhaust gas flow speed has a detrimental effect on the muffler performance. Beranek[6] gives examples in which the muffler attenuation is reduced from 35 dB to 6-10dB when the flow speed is increased from zero to 230 ft/sec. In typical industrial or diesel truck engine applications the exhaust flow speed can be 164 ft/sec to 390 ft/sec [6]. The effect of flow is related to the interaction of sound with turbulence and will be dependent on the internal design of the muffler.

3.2 Design Procedures

Design procedures for resonator mufflers are given in Beranek [6] and Bies and Hansen [7], but the process is complex. The procedure is to specify the resonant frequency of the muffler and the desired attenuation. A cavity volume is calculated and then the area of the openings (or connectors) between the exhaust pipe and the cavity must be calculated. Finally a wire or cloth screen to cover the openings must be chosen with the correct flow resistance to provide the correct damping (this reduces the maximum attenuation, but helps to reduce the effect of the pass bands where no insertion loss is achieved). Introducing tailpipes can significantly improve the muffler performance and more detailed consideration of acoustic transmission line theory [5,7] is required to properly design the tailpipe.

3.3 Typical Muffler Designs

Two typical reactive muffler designs are shown in Figure 3.1 and Figure 3.2. The first design, shown in Figure 3.1, is frequently chosen because of its low cost and because it causes a lower back pressure. The second design, shown in Figure 3.2, provides more attenuation and is typical of the design recommended by muffler manufacturers [6]. However there is no direction connection between the inlet and the outlet so back pressure is generated that can effect engine performance. This is sometimes referred to as a baffled muffler design.

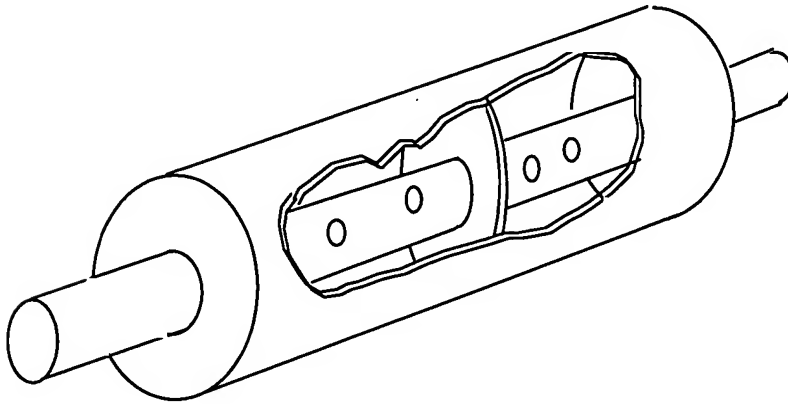


Figure 3.1 Sketch of a reactive muffler with two cavities and no flow restriction [6]

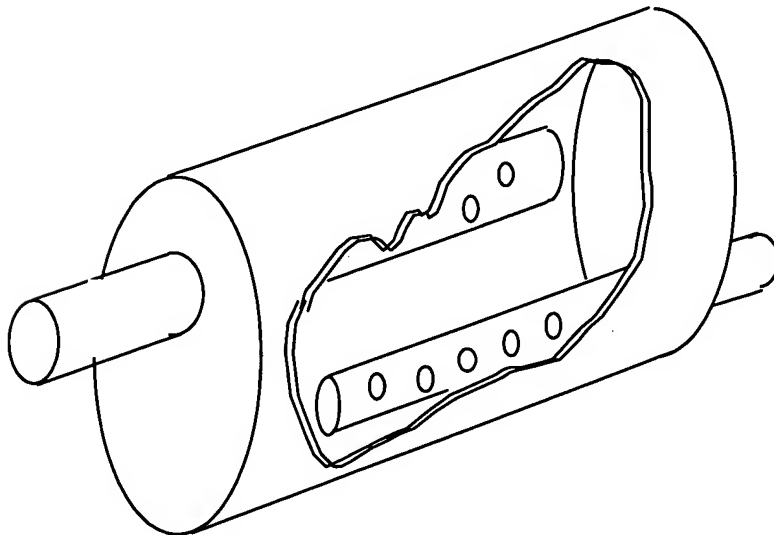


Figure 3.2 Sketch of a typical automotive reactive muffler in which there is no direct passage between the inlet and the exit [6]

From an acoustic stand point the muffler shown in Figure 3.1 has multiple cavities that are connected to the exhaust pipe by the holes illustrated on the central tube. When there is flow through the exhaust pipe a vortical flow can be created in each hole connecting the pipe to the cavity and this can have a significant effect on the connectivity between the two, reducing the insertion loss of the muffler. In Figure 3.2 the design differs in as much that there is no direct path for the exhaust gases to flow through the muffler, the flow speed is reduced and this reduces the vortex shedding that can cause problems in the design shown in Figure 3.1.

The maximum back pressure allowed for a Continental O-150 or a Lycoming 540 engine is 1 psi. Typical mufflers of the type shown in Figure 3.1 generate minimal back pressure, while those of the type shown in Figure 3.2 were measured during this study as having 1.4 ± 0.2 psi of back pressure (see section 7 for details).

3.4 Mufflers on General Aviation Aircraft

An interesting study was carried out by Heng et al [4] in which they designed a series of mufflers to reduce the noise from a general aviation aircraft. A Cessna 150 was used with a Continental O-200 engine operating with an engine speed of 2050 rpm at cruise and 2500 rpm on take off. At the outset of the study their initial calculations indicated that for smaller aircraft (<200hp) the engine noise dominated, but for larger aircraft (>300hp) the noise would be dominated by propeller noise. For the Cessna 150 (~100hp) their calculations showed that the engine noise would dominate by 10 dB on take off. They carried out exhaust muffler tests with an identical engine on a loaded test cell without the propeller and were able to claim a 13dB noise reduction due to an exhaust muffler by using their best design. However when the optimized muffler was fitted to the aircraft and flown it was found that the muffler made no measurable difference to the noise levels under the flight path during take off, leading to the conclusion that the propeller noise dominated the sound radiation in flight.

3.5 Mufflers Used during this Study

During this study 25 different muffler configurations were tested. Many of these were provided by boat owners or muffler manufacturers, and are listed in Table A3. In the second phase of the study, described in Section 7, three mufflers were used on different boats and with different mounting arrangements. Following the tests these three mufflers were cut in half and photographs of their internal design are shown below.



Figure 3.3(a) The Type 16 Muffler external view

Figure 3.3 (a) and (b) shows the Type 16 muffler (Walker Quietflow 22393) which was tested on Boats 15 and 16. This is a typical resonator muffler designed for automotive applications and was expected to have a low frequency attenuation characteristic that targets the noise generated at the engine firing frequency. Note how there are two separate cavities in this design and the inlet and outlet pipes extend into the cavity. Due

to its complexity of design it is not possible to estimate the performance of this muffler from its dimensions alone unless a numerical finite element analysis is carried out and accurate estimates can be made of the flow resistance in the perforations connecting the cavity.

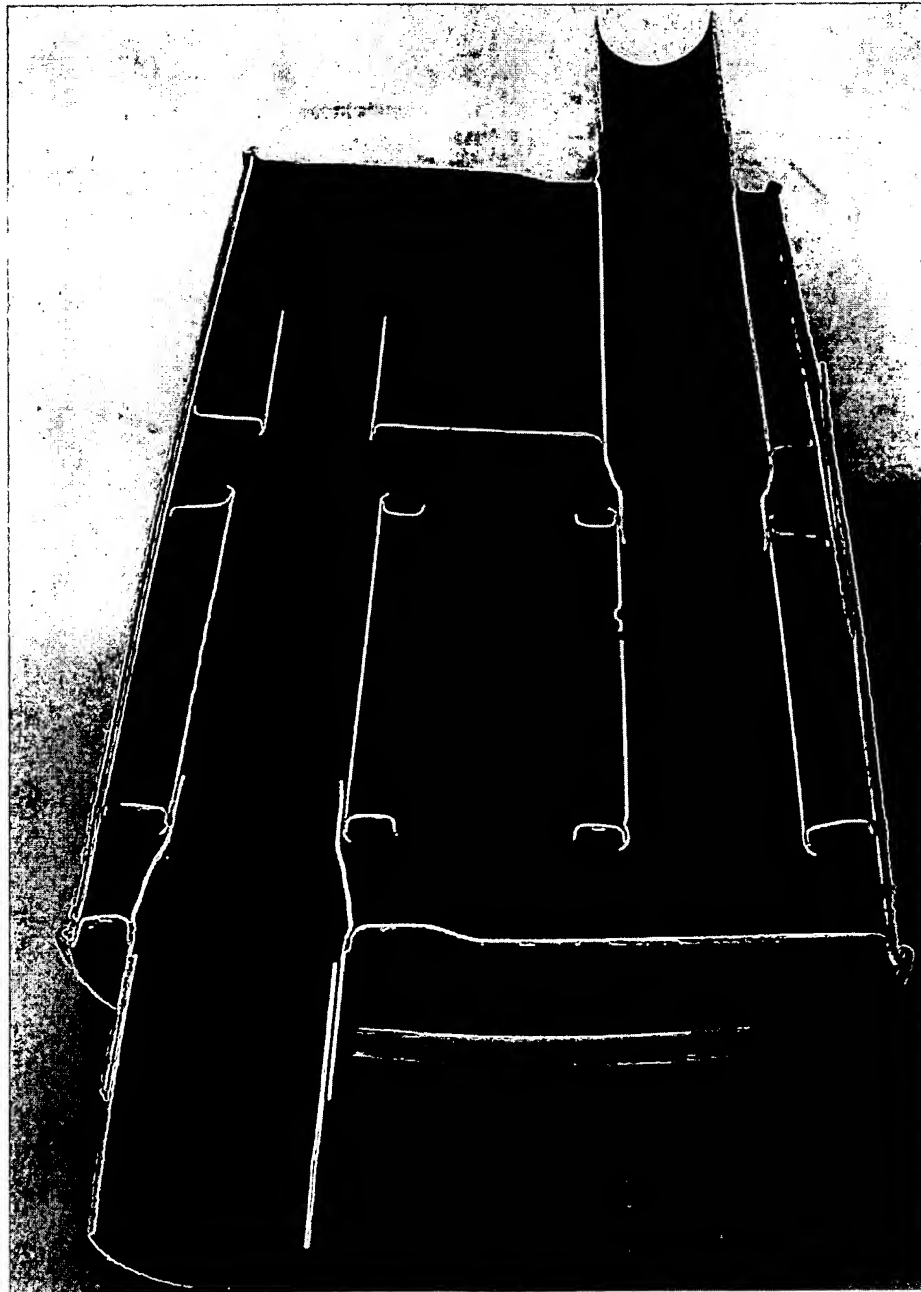


Figure 3.3(b) The Type 16 muffler, internal view

The Type 20 muffler (Vibrant 14", 6" diameter) was a cylindrical expansion chamber which was filled with sound absorbing material as shown in Figure 3.4 (a) and (b). This design will have a maximum low frequency attenuation at 240 Hz and pass band at around 480 Hz. The sound absorbing material will reduce the impact of the pass band and improve the attenuation at high frequencies, since it will act as a dissipative muffler. The area ratio of this muffler is 5.76 suggesting a peak attenuation of 10dB at 240 Hz.

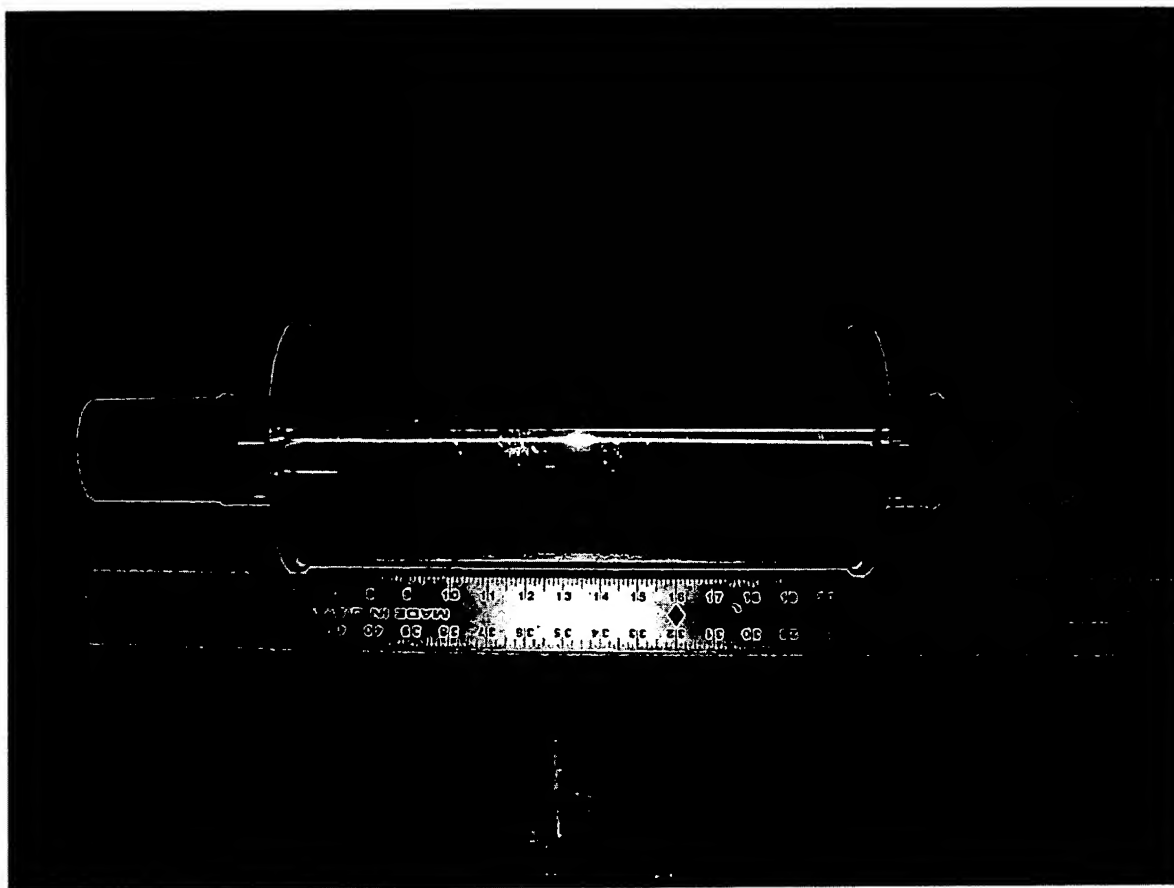


Figure 3.4 (a): The Type 20 Muffler external view

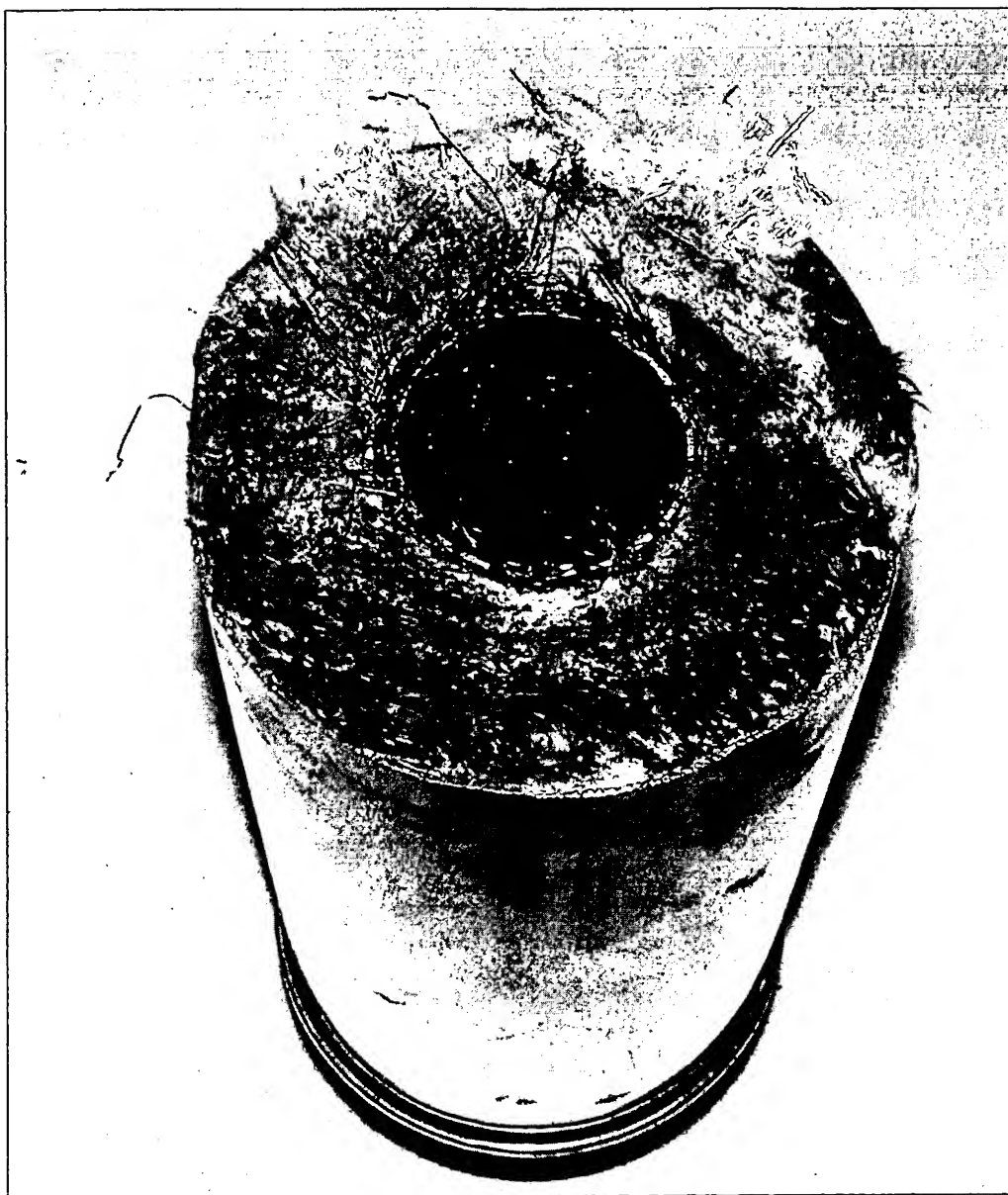


Figure 3.4 (b) The Type 20 muffler, cut away view.

In Figure 3.5 a diagram of the Type 7 muffler is shown. This again is an expansion chamber with sound absorbing material in the cavity. The length of the muffler is 14 inches and so the peak attenuation will be at 240 Hz and it will have a pass band at 480 Hz. The area ratio is 7 suggesting a peak attenuation of 11 dB.

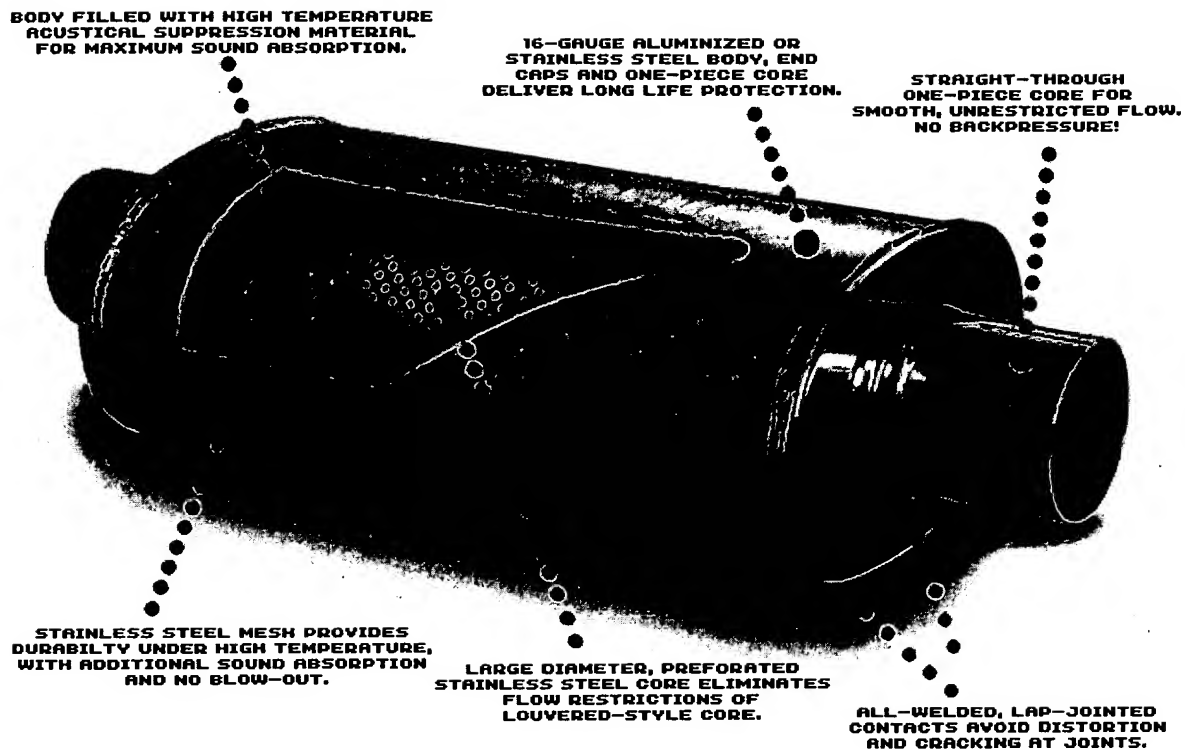


Figure 3.5 Cut out drawing of a Type 7 muffler.

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